TECHNICAL MEMORANDUM

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

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TECHNICAL PREPRINT prepared for

Heat Transfer and Fluid Mechanics Institute
University of California, Los Angeles, June 21-23, 1965

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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THE INCIPIENCE OF FLOW OSCILLATIONS IN FORCED-FLOW SUBCOOLED BOILING

by Frank A. Jeglic* and Kwang-Tzu Yang**

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ABSTRACT

FORCED

A study was made of the onset ~~of flow~~ oscillations occurring when ~~a~~ subcooled liquid undergoes ~~a~~ phase change under forced flow conditions in ~~a~~ single tube boiler. Experimental data were obtained with electrically heated tubes of variable length over a range of fluid velocities, temperatures, and pressures. The experiments were conducted at system pressures of 3 to 100 psia with degassed, demineralized water flowing vertically upward through a heated test tube. Visual studies were made in which boiling was simulated by injecting steam or air through the porous wall of a tube. A mathematical model predicting the necessary criterion for the incipience of oscillations was formulated on the basis of local rates of bubble growth and collapse. Good agreement was obtained between the experimental and the theoretical results. author

INTRODUCTION

The study of instabilities, occurring during the change of phase of a flowing liquid has been the object of many investigations in recent years. Experimental data show that various types of instabilities can result when boiling exists in a heated channel. High frequency pressure

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fluctuations have been observed in subcooled boilers (1). These are believed to be caused by the vapor voids collapsing in highly subcooled liquids. "Flow excursions," first reported by Ledinegg (2), can result from improper matching of the pump and boiler hydraulic characteristic. An instability may also be reflected in a surface temperature excursion, which is no more than the well-known "burnout" phenomenon, generally defined as the transition from the nucleate to film boiling regime. Another type of instability observed in boiling systems, results in oscillatory flow behavior. Often, the inception of flow oscillations determines the upper limit of the operating conditions of a given system. Consequently, much effort has been made to predict the onset of flow oscillations under various physical conditions. A review of the literature and state of the art is given in (3) and (4).

The objective of this investigation was to study the onset of flow oscillations in a single tube, forced flow, subcooled boiler. For all cases considered, the fluid bulk temperature was below the saturation temperature at both the exit and the inlet of the boiler. Demineralized, degassed water was used as the boiling fluid. Test sections consisted of electrically heated, vertical, Inconel X tubes of various lengths. All experimental tests were conducted in the pressure range of 3.0 to 100 psia, liquid bulk velocity of 2.2 to 3 ft/sec for various inlet bulk subcoolings. Some special test sections were constructed that permitted flow observation and photography. For some of the visual studies, porous wall tubing was used that allowed boiling simulation by injecting steam or air through the porous wall. Comparison between the results obtained with electrically heated test sections and the results of simulated boiling studies was made. The experimental observations were utilized in deriving a criterion, which predicts the necessary conditions for the onset of flow oscillations in subcooled boiling.

APPARATUS

General

A schematic diagram of the closed loop forced-flow boiling heat transfer facility is shown in figure 1 and is described in detail in (1). The system is pressurized or evacuated through the expansion tank by dry nitrogen gas or external vacuum pump, respectively. All component parts in contact with the test fluid were made of corrosion resistant materials to prevent fluid contamination and scale deposits. The fluid is circulated by a gear pump, powered by a variable speed drive. The power to the test section and the preheater is supplied by 250- and 70-kW interchangeable a.c. transformers, each regulated by a saturable reactor. The reactors provide fine continuous control of the power input. A counterflow heat exchanger serves as the system heat sink.

Test Sections

Electrically heated tubes. - The test sections were constructed of 0.020-in. wall Inconel X tubing with a 0.25-in. o.d. The tubing was expecially rolled to limit the wall thickness deviation to less than 3 percent of the nominal wall thickness and had a maximum surface roughness of 20 μin. The length of the heated portion of the primary test section was 21 in.; copper flanges were silver-soldered to both ends. Another test tube was provided with a sliding copper flange to facilitate variation of the heated length of the boiler. In both cases, the heated portion was preceded by at least a 15-diam unheated length to reduce the hydrodynamic entrance effects. The test section assembly was enclosed by a transparent shield to lessen external convective currents and provide protection in case of failure.

Transparent test sections. - Three special test sections were built for visual studies. One was to simulate the electrically heated tubes and was constructed of 0.21-in. i.d. porous-wall stainless-steel tubing. A short glass tubing of the same inside diameter was fused to the exit of the metallic tube. The porous-wall tube, with 5-μ-diam pores, was enclosed by a 1-in.-diam tube, which formed a chamber connected to a degassed steam or air supply. The other two test sections were annular passages, with 5/8-in. i.d. glass tubing constituting the outer boundary. In one case, two-phase flow was obtained by electrically heating a concentric, 1/4-in. o.d. Inconel tube. In the other, steam was injected through the porous wall of a 1/4-in. o.d. concentric tube.

Instrumentation

Strain-gage-type transducers with accuracy of 1/4 percent of full scale were used to measure the instantaneous pressures at various locations of the loop (see fig. 1). Flow transients were obtained with a turbine flow meter that had a response time of 3 to 5 msec. A 36-gage Chromel-Alumel thermocouple was spotwelded near the exit of the heated surface to obtain the surface temperature variation. The signals generated by the transducers, the turbine, and the thermocouple were continuously recorded on a multichennel oscillograph. The average values of pressures, surface and bulk temperatures, flow rate, and power input were measured by standard methods. All instrumentation is described in detail in (4).

A high-speed camera, capable of speeds up to 6000 frames/sec, was used to photograph the transparent test section during the run in the visual studies. A photo cell was mounted next to the test section and its signal recorded on the oscillograph. A light source could thus be recorded simultaneously on the film and the oscillograph. This enabled synchronization of the high-speed movies with the flow and pressure traces.

EXPERIMENTAL PROCEDURE

Prior to filling, the system was flushed with deionized water, purged with nitrogen, and evacuated. It was then filled with deionized, deaerated water. The liquid was circulated through the system and further degassed by boiling in the test section and venting to the atmosphere. The electrical resistivity of the test tube was measured a priori, and the values agreed well with those given in (5). All instruments were calibrated before installation and periodically checked.

The normal operating procedure consisted of setting the flow rate, the inlet bulk temperature, and the exit pressure to the desired values and then slowly increasing heat flux to the boiler (electrical power or steam injection rate) until the oscillations set in or net vapor was generated, which ever occurred sooner. Flow rate and exit pressure were adjusted during the run to maintain the preset value. For neutrally oscillating runs, the system was permitted to oscillate for a substantial period of time before the heat flux was reduced. The runs with increasing amplitude oscillations, however, were terminated by the automatic power shutoff, which was energized by the surface temperature excursion. Any one of the three controlled variables, flow rate, inlet bulk temperature, or exit pressure, was then changed and a new run begun. All recording instruments were turned on before the onset of oscillations and left on for the duration of the run.

EXPERIMENTAL RESULTS

Electrically Heated Tubes

The experimental results obtained with electrically heated tubes are tabulated in tables I and II. If the run was terminated because net quality vapor was being generated at the exit, it is so noted in the table. Two apparently different types of oscillations were recorded in subcooling boiling:

(1) Quickly developing oscillations, reaching maximum amplitude and remaining oscillatory indefinitely. Typical traces are shown in figure 2 where the variations of pressures and flow are given as a function of time.

(2) Oscillations with increasing amplitude, resulting in a surface temperature excursion. An example is shown in figure 3. It is believed that these oscillations would reach constant amplitude if the heat capacitance of the wall could be increased so that the excursion would be decreased sufficiently to prevent the power trip.

It can be seen from table I that for the range of this investigation the onset of flow oscillations in forced-flow subcooled boiling is a strong function of inlet subcooling and system pressure. An increase in inlet subcooling or a decrease in system pressure tends to induce subcooled boiling oscillations. It appears that, for a given system, a minimum inlet temperature and/or a minimum pressure is necessary to avoid these oscillations and permit generation of net quality vapor. The results obtained with the variable length test section, shown in table II, indicate that the decrease in the boiler tube length tends to decrease the exit bulk temperature at which the oscillations will develop. It should be noted that, whereas the heat flux increases with decrease in length, the total enthalpy rise of the fluid actually decreases.

Since the primary objective of this study was to determine the conditions at the onset of oscillations, little attention was paid to the amplitude and the period of the oscillations. In general, the amplitude was sufficiently high to allow the instability to be recognized. A quick examination of the traces reveals direct proportionality of the pressure and the frequency of oscillations. The velocity, heat flux, and bulk temperature, however, seem to have very little, if any, effect on the frequency.

Visual Studies

Initially, the porous-wall tube with glass extension was used in an attempt to duplicate the results obtained with electrically heated tube, while the flow pattern just downstream of the simulated boiler was being observed. The steam injection rate was not measured, but it was possible to calculate the heat input by the enthalpy increase of the fluid. The correspondence of conditions with the two test sections was excellent; not only did the oscillations occur at the same values, but also the traces were similar. A comparison of the recorded traces is illustrated in figure 4. The flow regime was observed to be bubbly at steady-state conditions, just preceding the onset of oscillations. As a small increase in the steam injection rate resulted in recording oscillations on the oscillograph, a vapor slug appeared in the transparent portion of the test section. The liquid-vapor interface along the wall at the leading end of the slug was quite wavy and irregular. As the slug proceeded up the tube, the liquid film on the wall became increasingly thinner with the interface continually growing smoother. The vapor slug ended abruptly and was followed by bubbly two-phase flow. Immediately behind the vapor slug, the bubbles were small and few but slowly grew in size and number until a new slug appeared. The length and the frequency of the slugs depended on the experimental conditions. However, for all cases the frequency of vapor slug formation corresponded with the frequency of the pressure and flow oscillations recorded on the oscillograph.

The high-speed movies obtained under a variety of experimental conditions were carefully examined and compared to the corresponding traces. It was concluded that, for every cycle, the bubbly-flow regime existed when the flow was at the maximum. The flow began to decrease just before the head of the vapor slug appeared in the transparent portion of the tube, continued to decrease as the slug grew and progressed toward the exit plenum, and reached a minimum before the appearance of the tail end of the vapor slug. A complete cycle is shown in figure 5, where the pictures, obtained with the high-speed camera, are superimposed on the trace. The photographs represent approximately a 1-in. length of the transparent portion of the tube, immediately downstream of the simulated boiling portion of the tube. Even though these movies do not show the actual development of the vapor slugs, they substantiate that flow oscillations and the "slugging" appeared simultaneously.

In a few runs, a nearly adiabatic, isothermal two-phase flow was examined by injecting air, instead of steam, through the porous wall of the tube. Most favorable conditions for oscillatory flow were selected, yet over the full range of air injection rate the system remained stable. As the air injection rate was increased, the flow regime changed from bubbly to wavy annular to smooth annular. Efforts were made in vain to attain a slugging flow pattern. This was an important observation which led to the conclusion that a two-component two-phase system will not result in oscillatory behavior in the range of this investigation. Thus, the analogy between single-component and two-component two-phase systems, so often employed, could lead to erroneous conclusions.

The flow pattern development and its behavior at the inception of oscillations was visually studied in the two annular test sections. The method of heating (electrical or steam injection) did not appear to have an effect on the fluid behavior. In both cases, an abrupt transition from bubbly to annular flow at the exit of the test section could be observed at the inception of oscillations. The transition was so sudden (depicted in fig. 6) that an interface between the two flow patterns could easily be defined, the annular flow portion giving the appearance of a vapor slug. This "interface" oscillated up and down, the frequency of oscillation agreeing well with the frequency recorded on the oscillograph.

Some Observations in Net Quality Boiling

When neutral oscillations were obtained in the subcooled boiling regime (corresponding to exit conditions), it was possible, under certain conditions, to suppress them by increasing the heat input. It was found that the unstable, subcooled boiling system could become unstable as the thermodynamic quality at the exit reached a positive value, and became unstable again at some higher heat-flux level. This phenomenon is shown in figure 7. It should be noted that the surface temperature oscillations in the two cases are different in nature. With the net quality, the temperature is similar to an excursion, usually observed and associated with the "burnout" and followed by a slow decrease. In the subcooled case, however, the temperature rises slowly and then suddenly drops at about the minimum flow, a behavior observed at the incipience of nucleate boiling. Some preliminary runs, in which an additional thermocouple further upstream was monitored on the oscillograph, yielded similar results. That is, conditions could be reached, such that the upstream surface temperature oscillated in a fashion characteristic at the incipience of boiling, while the exit thermocouple exhibited the "burnout" characteristics. Due to the oscillatory flow and therefore varying local quality, it is not surprising to attain this intermittent "burnout" phenomenon. It is believed that the periodic temperature excursions at the exit are the result of, rather than the cause of, flow oscillations. It is quite possible, that with insufficient instrumentation the quickly developing oscillations can go undetected, resulting in what is usually referred to as "premature burnout" or "submaximum burnout." It is also believed that the degree of thermal nonequilibrium between the two phases in the subcooled boiling region may be of great importance in its performance. Further studies are necessary to determine whether the thermal nonequilibrium is the driving force of flow oscillations.

DISCUSSION

Analytical Model

From the experimental data it was concluded that the "slugging" and flow oscillations always occurred simultaneously. If a vapor slug is to be formed, then the conditions at a given cross section must be such as to allow some bubble agglomeration. That means that the net effect of the high-temperature boundary layer and the subcooled liquid toward the center of the tube results in some net growth of the vapor voids formed on the heated surface. Then, if the "slugging" is to occur, the net bubble growth rate at a cross section must be greater than zero, or in the limit equal to zero. This is postulated as the necessary condition for flow oscillations in subcooled boiling.

Scriven (6), Forster and Zuber (7), and Plesset and Zwick (8) have all derived expressions for the asymptotic long-time growth of a vapor bubble. Yang and Clark (9) arrived at a simple expression for the bubble growth constant; their solution agreed well with those in (6) to (8). By using the results of (9), the bubble growth rate is given by

$$\dot{R} = \frac{\sqrt{\pi}}{2} \frac{\rho_l c_l}{\rho_v h_{fg}} \sqrt{\frac{\alpha_l}{\theta}} (t - t_s) \tag{1}$$

The average bubble growth rate over any cross section of the tube, assuming constant properties, is then

$$\dot{R}_{\alpha v} = \frac{\sqrt{\pi\alpha_l}}{r_i^2\ \sqrt{\theta}}\ \frac{\rho_l c_l}{\rho_v h_{fg}} \int_0^{r_i} (t - t_s)\ r\ dr \tag{2}$$

If the necessary condition for oscillations is satisfied, the average bubble growth rate $\dot{R}_{\alpha v}$ must be equal to zero. Hence,

$$\int_0^{r_i} (t - t_s)\ r\ dr = 0 \tag{3}$$

where t is the local temperature of the liquid and t_s is the interface temperature.

Calculation of Necessary Stability Criterion

To evaluate the integral in equation (3), it was assumed that the bubble formation has a negligible effect on the temperature profile. This implies that the fluid can sustain itself in the liquid phase until the onset of oscillations. It was observed experimentally that, indeed, when the oscillations did occur in subcooled boiling regime, the bubbly flow pattern existed in a very short portion of the tube. By utilizing this assumption, the temperature profile was calculated for a given energy input. Its effect on bubble behavior was then examined, and the integral in equation (3) was evaluated. The energy input value was then changed until the necessary criterion, given by equation (3), was satisfied.

Several analyses for the determination of the temperature profile across a fully developed turbulent boundary layer exist in the literature (10). However, the results of Deissler (11) were used herein, primarily for convenience and also because his analysis takes the variation of viscosity into account and applies well to water. All calculations were performed on IBM 7094 digital computer. For details, the reader is referred to (4).

Comparison of Theoretical and Experimental Results

To determine the heat flux that satisfies the necessary criterion for instability (eq. (3)), inlet bulk temperature, system pressure, and boiler length were taken as independent variables. The computed necessary heat flux is plotted against inlet bulk temperature in figure 8 for different velocities, with experimental data superimposed on the graphs. Similarly, the effects of pressure (saturation temperature) and boiler length are shown in figures 9 and 10, respectively.

It can be seen from the figures that, in general, the agreement between the experimental and theoretical results is quite good. At small subcooling, the experimental data deviate somewhat from the predicted values. Under these conditions, the heat input necessary to generate net vapor at the exit is much lower than it is at large subcoolings, resulting in a lower axial rate of change of void fraction, similar to that depicted in figure 11. It is speculated, that if the oscillations are to occur in subcooled boiling, in addition to satisfying the necessary criterion, the transition from bubbly to annular flow pattern must be abrupt (fig. 6), that is, the rate of change of void fraction must have some minimum value. Further experimental evidence is necessary to prove or disprove this argument, which is based on limited experimental data and is presented here more as a possibility than a fact.

A similar argument can be presented to explain the absence of oscillations at higher pressures. The increase in heat flux necessary to obtain net quality at higher pressure is smaller than the corresponding decrease in the liquid-vapor density ratio. Thus, the net effect of pressure increase would be a lower axial rate of change of void fraction, an unfavorable condition for onset of flow oscillations in subcooled boiling.

SUMMARY

The experimental values of heat flux at which flow oscillations occurred were compared to the values calculated from the necessary criterion for incipience of oscillations that was derived on the basis of local rates of bubble growth and collapse. The theoretical and experimental results agreed well. The experimental results obtained in this investigation may be summarized as follows:

1. Basically, two types of oscillations were observed in subcooled boiling with electrically heated test sections: constant-amplitude oscillations and oscillations with increasing amplitude that resulted in surface temperature excursion. It is believed, that the excursion was the direct result of the relatively low heat capacitance of the tube.

2. With the aid of high-speed movies, flow patterns at the inception of oscillations were studied. It was observed that, when flow oscillations were present, a quick transition from the bubbly- to an annular-type flow pattern existed in the test section. The interface oscillated

up and down the tube, in frequency with flow and pressure oscillations.

3. Comparable oscillatory behavior was obtained when boiling was simulated by steam injection through a porous wall. When two-phase flow was attained by injecting air through the porous wall, however, the system remained stable for all cases investigated.

4. An oscillatory, subcooled boiling system could be stabilized by increasing heat flux and thus generating net quality. The system would remain nonoscillatory until some new heat flux value would be reached. The surface temperature oscillations in subcooled and net quality vapor generation are entirely different in shape.

5. With other variables held constant, a decrease in system pressure and an increase in inlet subcooling tend to destablize the subcooled boiling system.

NOMENCLATURE

c_l	specific heat of liquid
F	flow rate
h_{fg}	latent heat of evaporation
P_c	condenser pressure
P_{ex}	exit pressure
P_{in}	inlet pressure
P_{ph}	preheater pressure
$\dot{R}$	bubble growth rate
$\dot{R}_{av}$	average bubble growth rate
r	radius
r_i	inside tube radius

T_i heating surface temperature

T_{in} inlet bulk temperature

t local temperature of liquid

t_s interface temperature

α_2 thermal diffusivity of liquid

θ time

ρ_l density of liquid

ρ_v density of vapor

REFERENCES

1. Jeglic, F. A., Stone, J. R., and Gray, V. H.: Experimental Study of Subcooled Boiling of Water in Forced Flow at Low Pressures. Proprosed NASA Technical Note.
2. Ledinegg, M.: Unstabilitaet der Stroemung bei Natuerlichem und Zwangumlauf. Waerme, vol. 61, no. 48, Nov. 26, 1938, pp. 891-898.
3. Gouse, William S., Jr.: Two-Phase Gas-Liquid Flow Oscillations, Preliminary Survey. Report DSR 8734-5, M.I.T., July 1964.
4. Jeglic, Frank A.: The Onset of Oscillations in Forced Flow Subcooled Boiling. Ph.D. Thesis, Univ. of Notre Dame, October 1964.
5. Anon.: Engineering Properties of Inconel and Inconel "X", Tech. Bull. T-7, International Nickel Co., September 1959.
6. Scriven, L. E.: On the Dynamics of Phase Growth. Chem. Eng. Sci., vol. 10, 1959, pp. 1-13.
7. Forster, H. K., and Zuber, N.: Growth of a Vapor Bubble in a Superheated Liquid. Jour. Appl. Phys., vol. 25, no. 4, Apr. 1954, pp. 474-478.

8. Plesset, M. S., and Zwick, S. A.: The Growth of Vapor Bubbles in Superheated Liquids. Jour. Appl. Phys., vol. 25, no. 4, Apr. 1954, pp. 493-500.

9. Yang, W. J., and Clark, J. A.: On the Application of the Source Theory to the Solution of Problems Involving Phase Change. Pt. I - Growth and Collapse of Bubbles. Jour. Heat Trans. (ASME Trans.), ser. C., vol. 86, no. 2, May 1964, pp. 207-212.

10. Kestin, J., and Richardson, P. D.: Heat Transfer Across Turbulent, Incompressible Boundary Layers. Int. Jour. Heat and Mass Transfer, vol. 6, no. 2, Feb. 1963, pp. 147-189.

11. Deissler, R. G.: Heat Transfer and Fluid Friction for Fully Developed Turbulent Flow of Air and Supercritical Water with Variable Fluid Properties. ASME Trans., vol. 76, no. 1, Jan. 1954, pp. 73-85.

TABLE I. - EXPERIMENTAL DATA WITH CONSTANT LENGTH, ELECTRICALLY HEATED TUBE

[Tube i.d., 0.21 in.; length, 21.0 in.]

Run	Inlet bulk temperature, °F	Exit bulk temperature, °F	Exit pressure, psia (a)	Inlet liquid velocity, ft/sec	Heat flux (at onset of oscillations) Btu/(sec)(sq ft)	Comments
20 - 1-1	79	222	20.0	2.20	49.1	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 1-2	148	223		2.20	34.1	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 1-3	175	---		2.20	----	Net quality vapor easily obtained
20 - 2-1	68	211		4.00	93.5	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 2-1a	67	208		4.00	91.7	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 2-2	94	216		4.00	79.0	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 2-3	115	219		4.00	68.5	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 2-4	146	---		4.00	55.8	Constant-amplitude oscillations in flow, pressures, and surface temperature
20 - 2-5	183	---		4.00	----	Net quality vapor easily obtained
20 - 3-1	61	211		6.25	146.0	Oscillations with increasing amplitude that resulted in temperature excursion
20 - 3-2	91	220		6.25	129	Oscillations with increasing amplitude that resulted in temperature excursion
20 - 3-3	108	222		6.25	113	Oscillations with increasing amplitude that resulted in temperature excursion
20 - 3-4	130	---		6.25	94.7	Oscillations with increasing amplitude that resulted in temperature excursion
20 - 3-5	150	---		6.25	87.6	Irregular oscillations apparent; net quality easily obtained
20 - 3-6	182	---		6.25	-----	Net quality vapor easily obtained
20 - 4-1	64	219		8.25	201	Oscillations with increasing amplitude that resulted in temperature excursion
20 - 4-2	99	217		8.25	161	Oscillations with increasing amplitude that resulted in temperature excursion
20 - 4-3	124	---		8.25	-----	No oscillations detected in subcooled regime; net quality easily obtained
40 - 1-1	80	---	40.0	2.20	75.6	Irregular oscillations apparent; net quality easily obtained
40 - 1-2	152	---	40.0	2.20	-----	Net quality vapor easily obtained
40 - 2-1	70	266	40.0	4.00	125	Constant-amplitude oscillations in flow, pressures, and surface temperature
40 - 2-2	100	---	40.0	4.00	-----	Net quality vapor easily obtained
V - 1-1	80	140	3.0	2.20	19.7	Constant-amplitude oscillations in flow, pressures, and surface temperature
V - 2-1	71	140	3.0	4.00	39.0	Constant-amplitude oscillations in flow, pressures, and surface temperature
V - 3-1	70	140	3.0	6.25	62.5	Oscillations with increasing amplitude that resulted in temperature excursion
V - 4-1	70	140	3.0	8.25	85.6	Oscillations with increasing amplitude that resulted in temperature excursion

[a] For all runs at 60- and 100-psia exit pressure, over the same range of liquid velocities and maximum inlet subcooling, net quality was easily obtained without observing any oscillatory behavior in the sub-cooled regime.

TABLE II. - EXPERIMENTAL DATA WITH VARIABLE

LENGTH, ELECTRICALLY HEATED TUBE

(Tube i.d., 0.21 in.)

Run	Test section length, in.	Inlet bulk temperature, °F	Exit bulk temperature, °F	Exit pressure, psia	Inlet liquid velocity, ft/sec	Heat flux (at onset of oscillations, Btu/(sec)(sq ft)
1-1	18.25	72	216	20.0	2.20	60.8
1-2	14.0	70	211	20.0	2.20	76.8
1-3	10.5	72	214	20.0	2.20	98.2
1-4	10.0	70	208	20.0	2.20	104
1-5	7.0	70	199	20.0	2.20	147
1-6	4.0	72	189	20.0	2.20	234

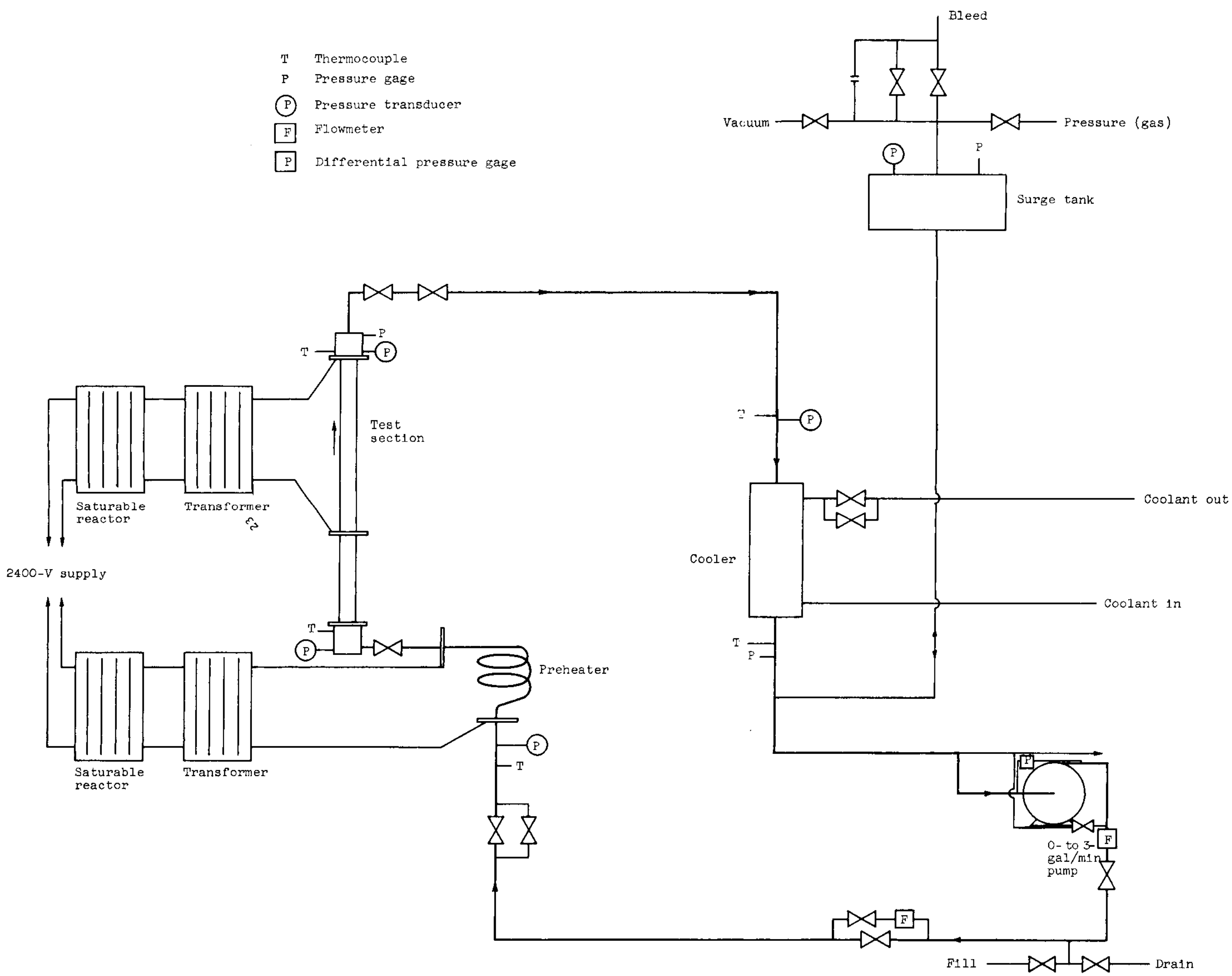
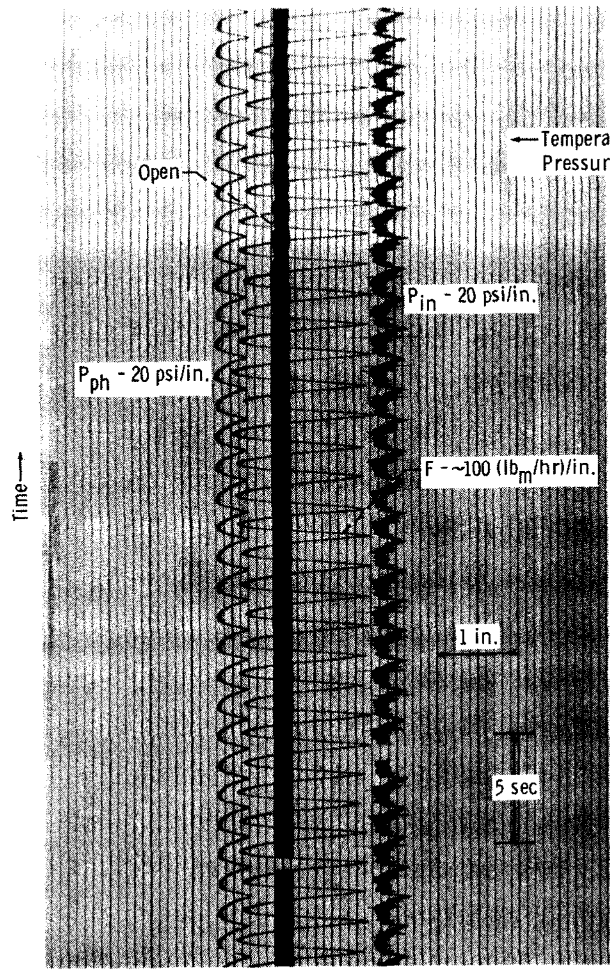
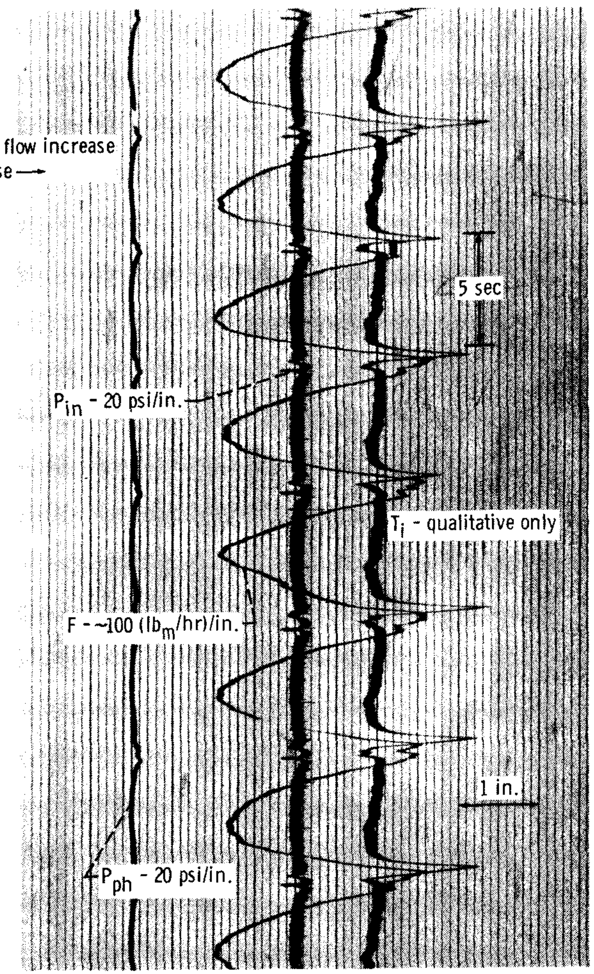


Figure 1. - Schematic of boiling heat-transfer facility.

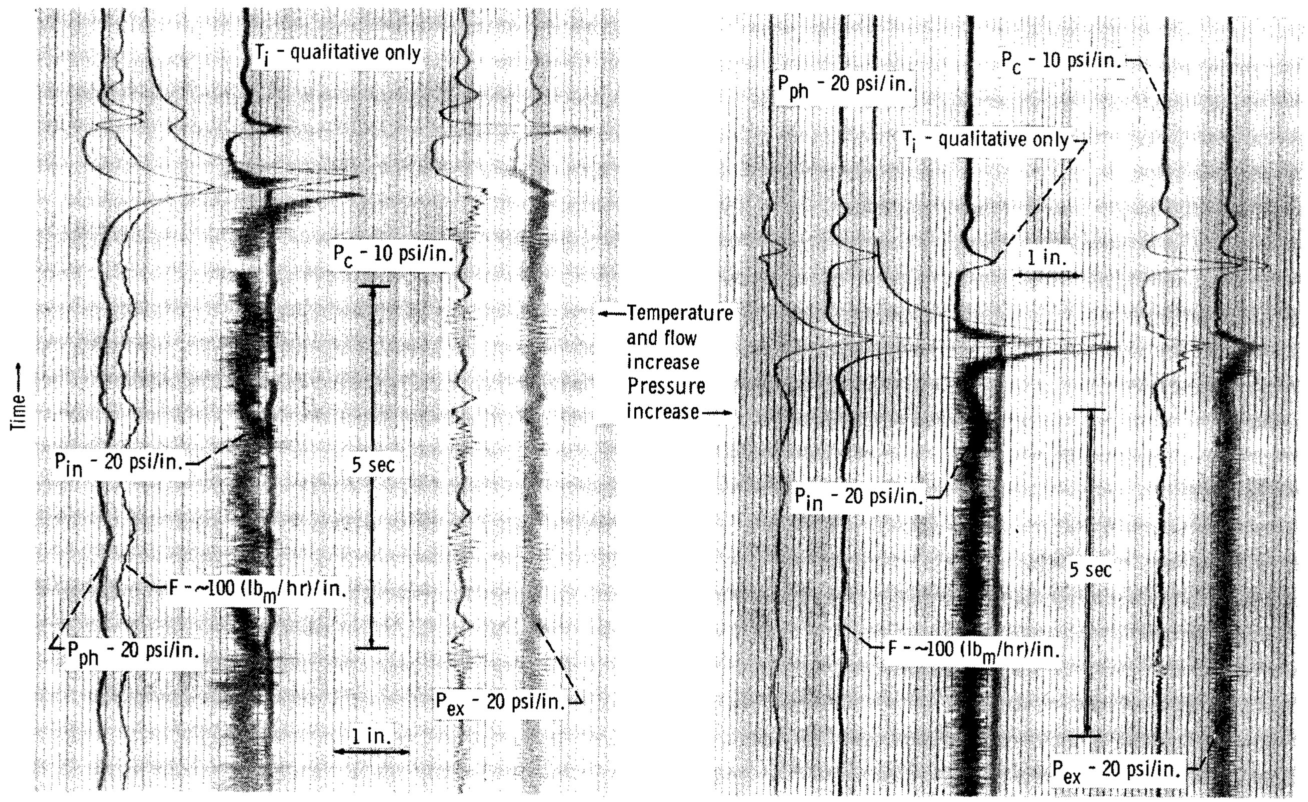


(a) Run 20-1-2.



(b) Run V-1-1.

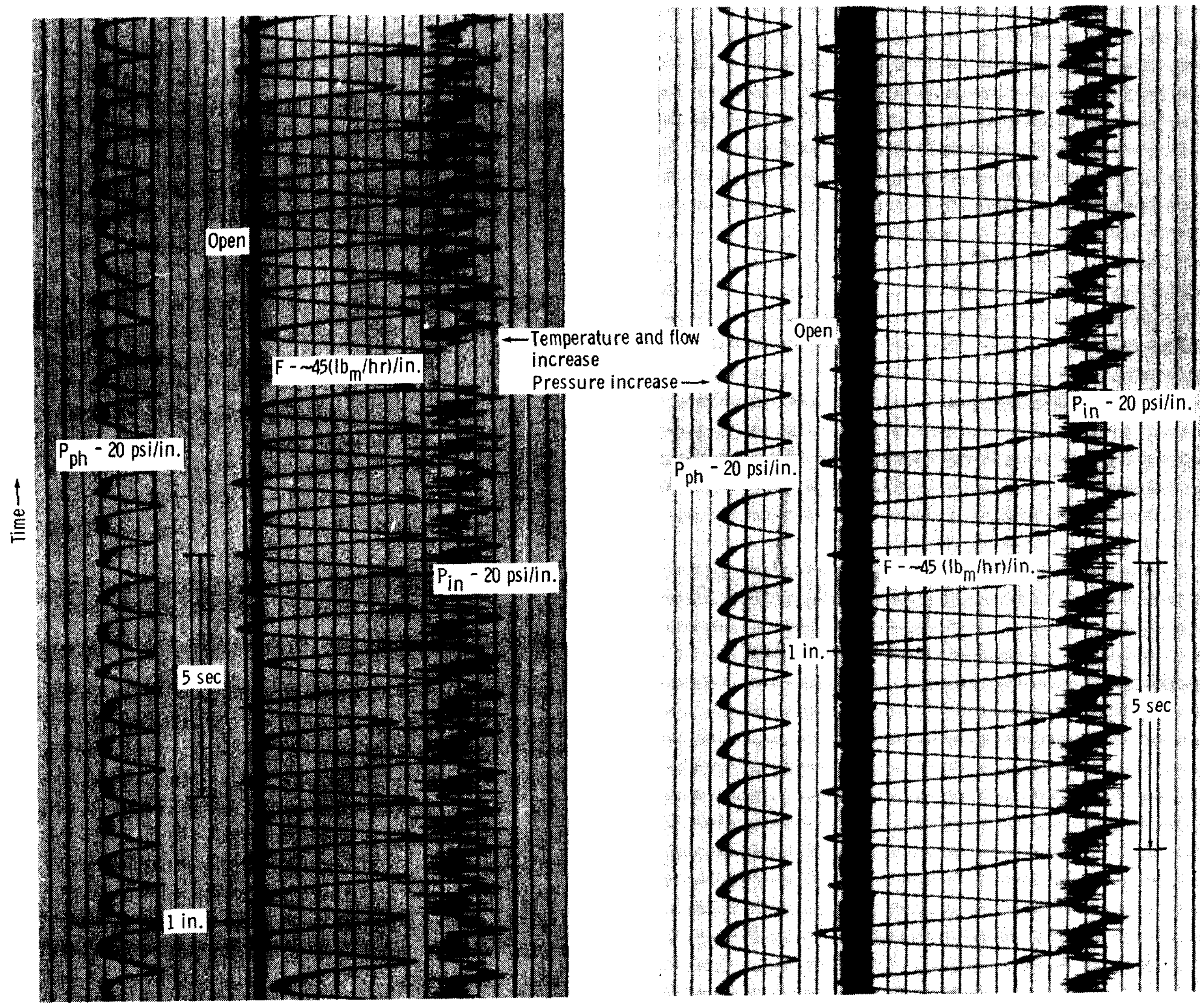
Figure 2. - Typical traces illustrating constant amplitude oscillations.



(a) Run 20-3-1.

(b) Run 20-4-2.

Figure 3. - Typical traces illustrating oscillations with increasing amplitude and resulting in surface temperature excursion.



(a) Steam injection.

(b) Electrical heating.

Figure 4. - Comparison of traces obtained with electrically heated test section and with steam injection.

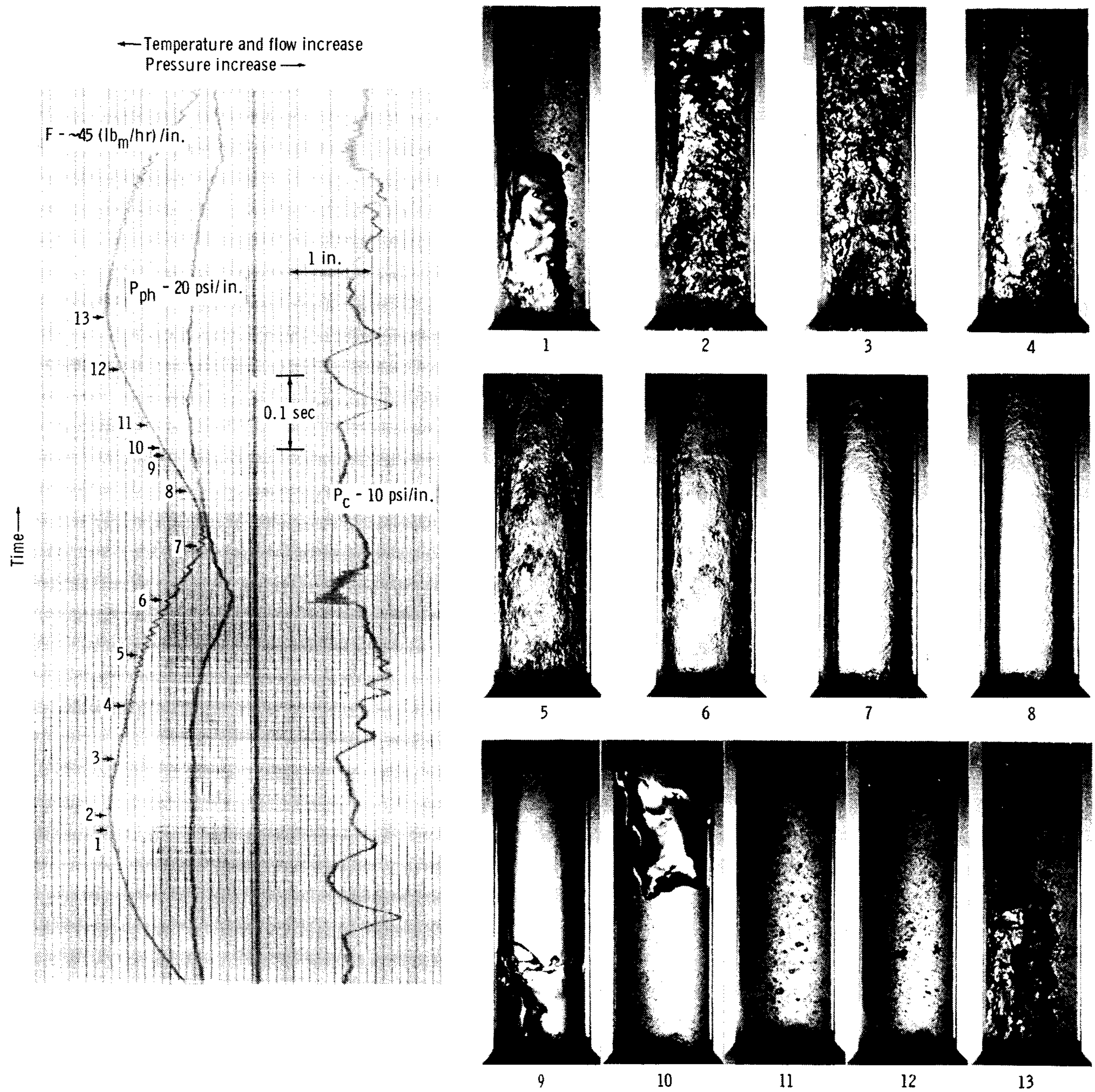


Figure 5. - Two-phase single-component flow behavior under oscillatory conditions obtained with tubular, porous-wall test section.

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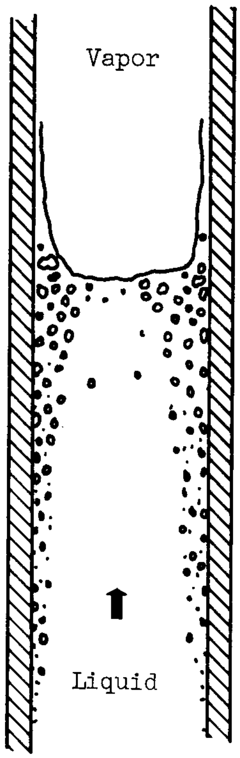

Figure 6. - Flow pattern development favorable for inception of oscillations.

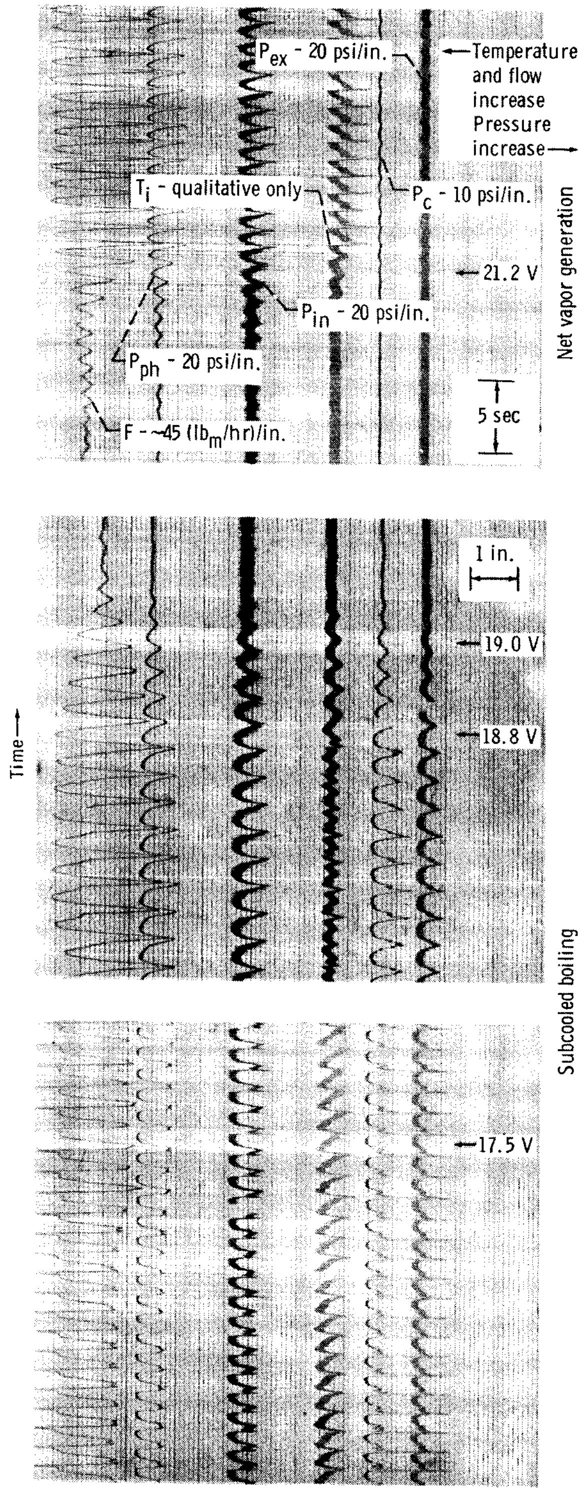

Figure 7. - Typical flow, pressure, and surface temperature behavior in transition region between subcooled boiling and net vapor generation.

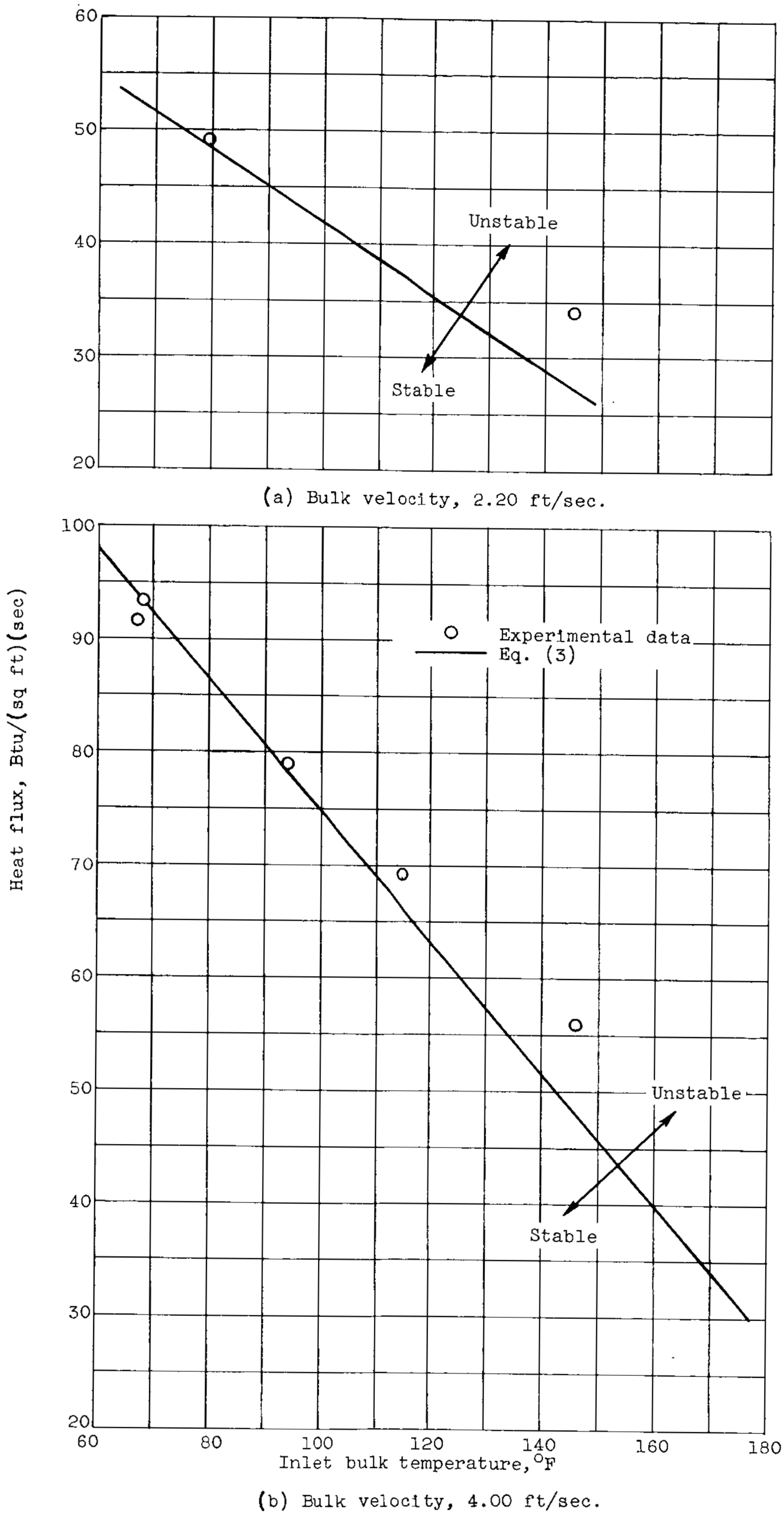

Figure 8. - Comparison of experimentally determined and theoretically predicted necessary heat flux for onset of oscillations as function of inlet bulk temperature. Exit pressure, 20 psia.

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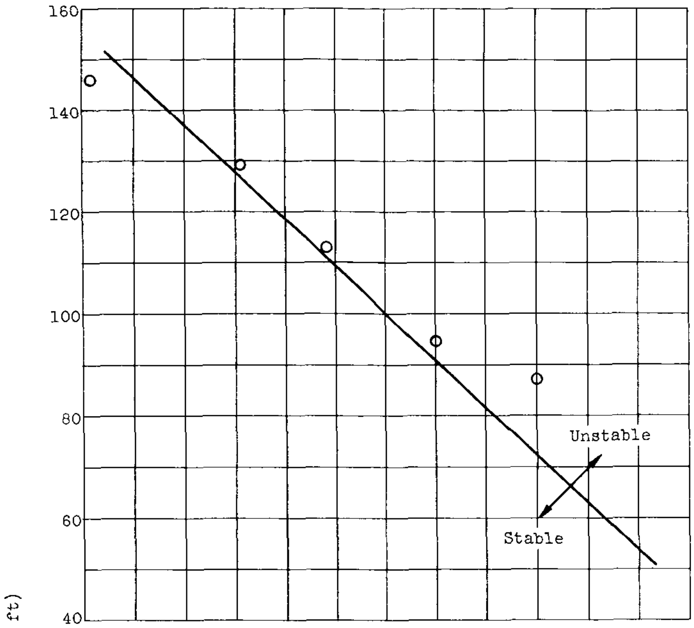
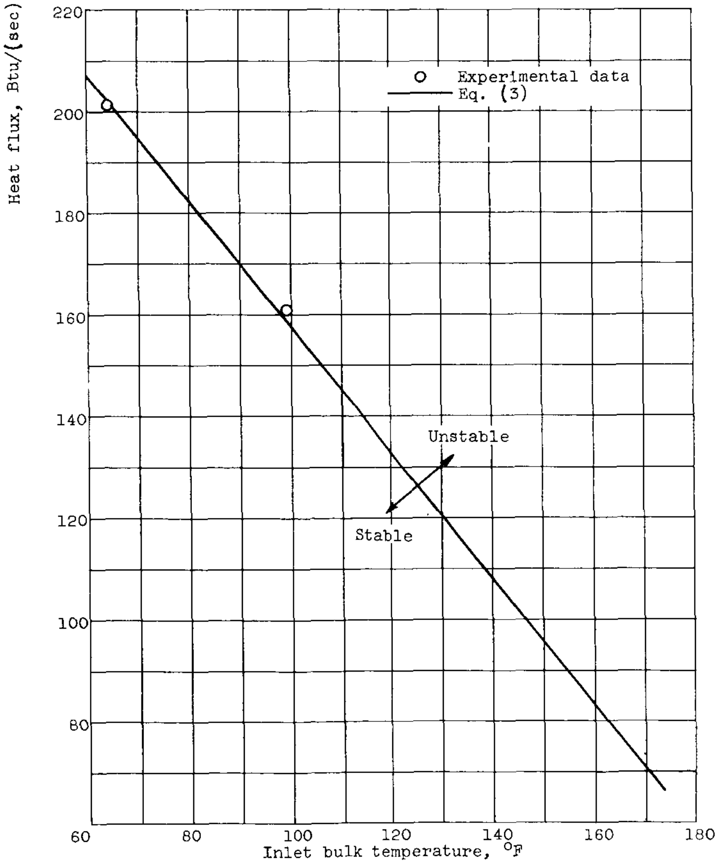


(c) Bulk velocity, 6.25 ft/sec.



(d) Bulk velocity, 8.25 ft/sec.

Figure 8. - Concluded. Comparison of experimentally determined and theoretically predicted necessary heat flux for onset of oscillations as function of inlet bulk temperature. Exit pressure, 20 psia.

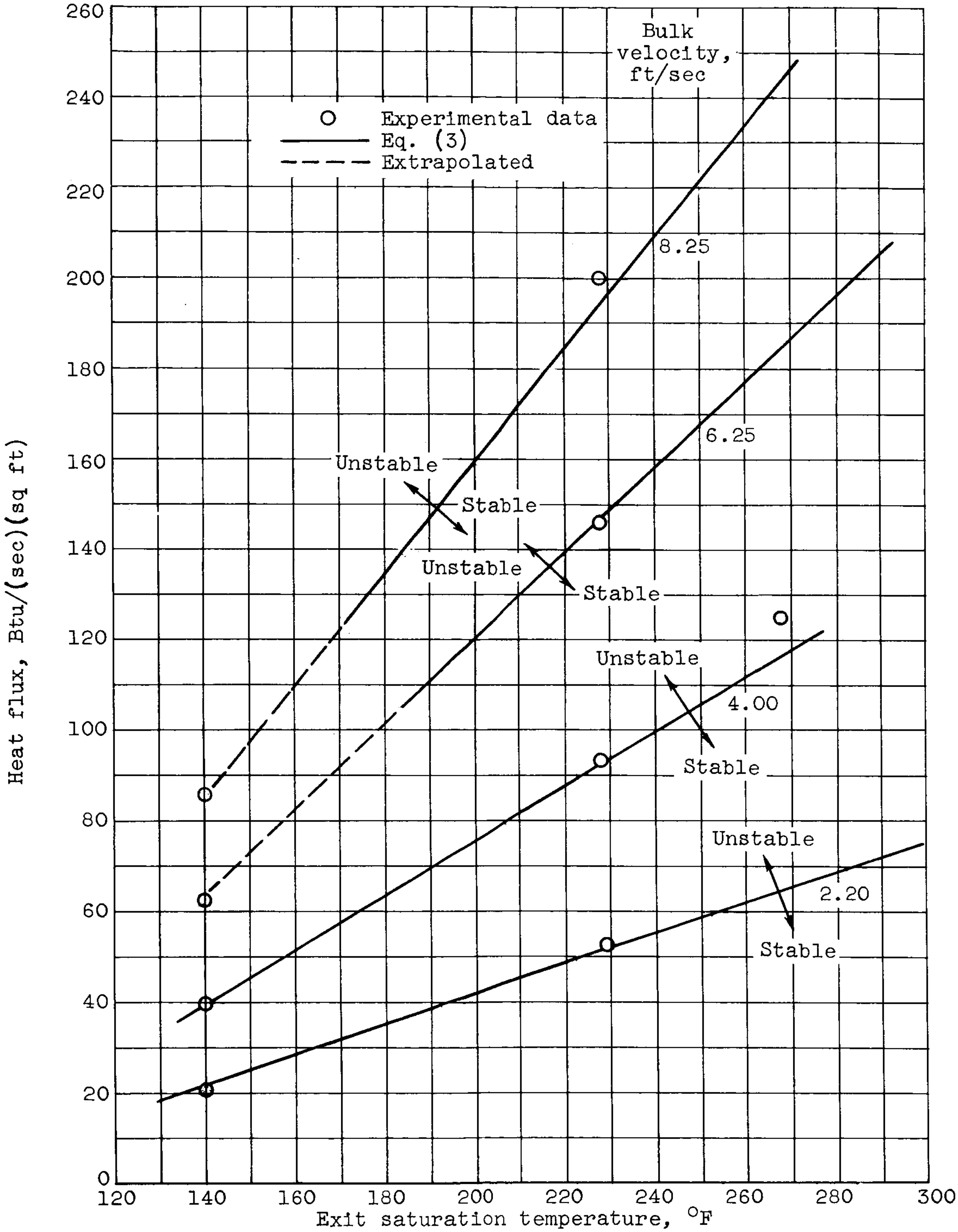


Figure 9. - Comparison of experimentally determined and theoretically predicted necessary heat flux for onset of oscillations as function of exit pressure (saturation temperature). Inlet bulk temperature, ~ 70° F.

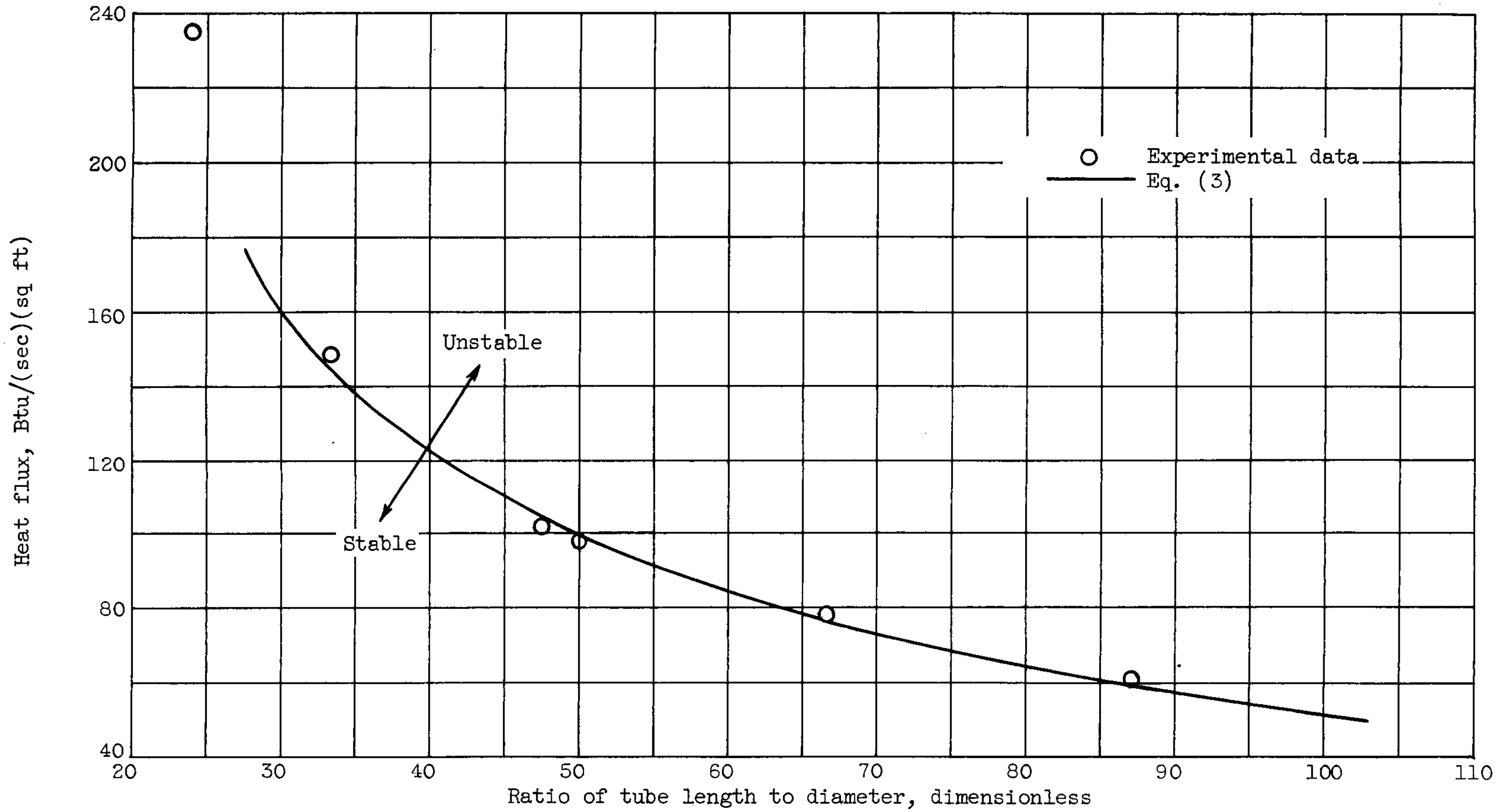


Figure 10. - Comparison of experimentally determined and theoretically predicted necessary heat flux for onset of oscillations as function of boiler length. Bulk velocity, 2.20 ft/sec; inlet bulk temperature, 70° F; exit pressure, 20.0 psia.

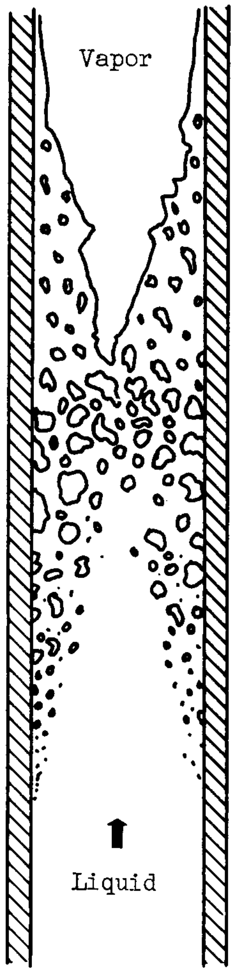


Figure 11. - Flow pattern development unfavorable for inception of oscillations.